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RESTORATIVE-ITERATIVE INITIALIZATION
FOR A GLOBAL PREDICTION MODEL

by

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ABSTRACT

A restorative-iterative proceedure is tested in initializing the height and wind fields for a global barotropic prediction model. Real 500 mb data is used as the basis of initial height values in the mid latitudes and as the basis of the initial streamfunction values in the tropics. The proceedure is tested for the case of frictionless and adiabatic flow and for the case where friction and a simulated heating function is included. In addition, experiments were performed in which an "observed" divergent wind was added in the tropics. Results are very encouraging in the sense that the amplitudes of the external inertia-gravity motions excited due to initial imbalance between the mass and wind fields are reduced considerably with the use of the proceedure.

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ABSTRACT

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ACKNOWLEDGEMENT

Appreciation is given to CAPT S. Houston, Commander, FNWC, for the financial support of this work.

Acknowledgement is also given to Dr. A. Arakawa whose original suggestions inspired these experiments. Without the computer facility of the W.R. Church Computer Center the work would not have been possible.

1. Operational numerical weather prediction is on the threshold of using rather sophisticated global prediction models. This is being made feasible by the rapid expansion of computing capacity as well as development related to general circulation research. But unlike the general circulation model the operational model must begin from real data. For the foreseeable future the initial data will be somewhat fragmentary in nature so this naturally poses some difficult problems. For example, one such problem might be; given a certain type of data, i.e., observations of mass alone, wind alone, or some mixture, what method should be used to initialize the missing type of data so that a global model will not suffer during the early part of a forecast run from excitation of excessive inertia-gravity motions? This paper will be concerned with this topic.

As a general guide the geostrophic adjustment theory indicates that for mid-latitude motions of synoptic scale the wind does have a strong tendency to adjust to a given or observed mass field. In other words strong changes takes place in the wind field rather than the mass field as the adjustment is occuring. In the tropics rather the opposite may occur. For a theoretical treatment of these subjects see (Cahn, 1945, Obukhov, 1949, Bolin, 1953, or Washington, 1964). From quasi-geostrophic theory, most valid certainly in the higher latitudes, certain balance relationships are derived which allow a computation of such a balanced wind if the mass observations are adequate. Both non-divergent and divergent parts of the wind can be computed. On the other hand a mass field may be computed from a non-divergent wind if it is adequately observed. This may be applicable in the lower latitudes.

Such computed initial winds are presently being used in operational mid-latitude models (Shuman and Hovermale, 1968, Kesel and Winninghoff, 1971) but are not adequate for the tropics. Also difficulties do arise in the computation of such winds. The equations in the most sophisticated technique - the total non-linear balance equation and the consistent form of the omega equation - are not easy to solve. There is the ellipticity difficulty and if another coordinate system other than the pressure system is used in the vertical much complication arises.

Therefore in the past five years another general method, proposals for which have been discussed by Nitta and Hovermale, 1969, Miyakoda and Moyer, 1968, Winninghoff, 1968, Nitta, 1969, Charney, Halem and Jastrow, 1969,

Jastrow and Halem, 1970, and Mesinger, 1971, has been proposed as an alternate method of achieving a total balanced condition. This method which we will refer to as the "restorative-iterative" method, though all of the above references do not use explicit restoration, is one in which the principle involved is the use of the equations in an iterative sense either at a fixed time level or even in a four dimensional sense in which data is assimilated into a running model. This allows for the natural adjustment mechanism itself to achieve the desired balance or a time scheme such as the Euler-backward scheme may be used for the same purpose. The method has the advantage of mathematical simplicity and complete consistency with the prediction model though at present it is expensive in computer time. This disadvantage, however, will very soon be removed by computers such as the ILLIAC IV.

This paper will be concerned with this restorative-iterative proceedure but only at a single time level. However, it will be applied to the entire globe.

2. Model

The experiments to be reported here used a simple free surface barotropic prediction model. The equations for this model are,

$$\frac{\partial (uh)}{\partial t} + \frac{1}{a \cos \phi}\left[\frac{\partial}{\partial \lambda} uuh + \frac{\partial}{\partial \phi} uvh \cos \phi\right] - \frac{uvh \tan \phi}{a}$$

$$- fvh = - \frac{h}{a \cos \phi} \frac{\partial}{\partial \lambda} gh \tag{1}$$

$$\frac{\partial (vh)}{\partial t} + \frac{1}{a \cos \phi}\left[\frac{\partial}{\partial \lambda} vuh + \frac{\partial}{\partial \phi} vvh \cos \phi\right] + \frac{uuh \tan \phi}{a}$$

$$- fuh = - \frac{h}{a} \frac{\partial}{\partial \phi} gh \tag{2}$$

$$\frac{\partial h}{\partial t} + \frac{1}{a \cos \phi}\left[\frac{\partial}{\partial \lambda} uh + \frac{\partial}{\partial \phi} vh \cos \phi\right] = 0 \tag{3}$$

Equations (1) and (2) are the zonal and meridional momentum equations in flux form. Equation (3) is the continuity equation. Symbols are,

u - zonal component of wind

v - meridional component of wind

h - height of the free surface

$\partial\lambda$ - increment in longitude

a - radius of the earth

$\partial\phi$ - increment in latitude

ϕ - latitude

f - coriolis parameter

g - acceleration due to gravity.

The finite difference equations corresponding to equations (1), (2), and (3) are written on a staggered grid where the variables are located relative to one another as shown in figure 1, with h alone carried at the poles. The increment of latitude and longitude used was five degrees. Therefore, there are 1260 points (36 x 35) to cover the globe. The differencing used is the Arakawa method providing no spurious energy growth due to the effect of advection. Two schemes in time were used as explained in the discussion of the experiments. The spatial differencing is shown in Appendix A.

↑			↑
← h	uv	h	uv →
uv	h	uv	h
← h	uv	h	uv →
↓			↓

h at poles

Figure 1.

The time step used is 15 minutes. This was possible in spite of the 40 kilometer distance between grid points at 85° N and S, because of a proceedure to average the effect of inertia-gravity waves of high frequency in the zonal direction used by Arakawa (Langlois and Kwok, 1969).

A coefficient is defined,

$$A_j = .125(D_j - 1)/\tilde{D}_j \tag{4}$$

where $D_j \equiv 1/\cos\phi$ and $\tilde{D}_j$ is the greatest integer value of D_j not greater than D_j. If $D_j \leq 1$ no averaging is done. If D_j is between 1 and 2 uh in equation (3) and in the advective terms of equations (1) and (2) and h in the pressure gradient term in equation (1) is replaced by,

$$uh^{1}_{ij} = uh_{ij} + A_j\left(uh_{i+1j} + uh_{i-1j} - 2\,uh_{ij}\right) \tag{5}$$

For $N \leq D_j < N+1$,

$$uh^{N}_{ij} = uh^{N-1}_{ij} + A_j\left(uh^{n-1}_{i+ij} + uh^{N-1}_{i-ij} - 2\,uh^{N-1}_{ij}\right) \tag{6}$$

is used.

3. Experimental Results

A number of experiments were conducted with the global barotropic model to test the effects of a restorative-iterative initialization proceedure.

The basic data used was a 500 mb. height field read from the Fleet Numerical Weather Central's master file for 00Z, January 8, 1971. This field was analized by the FNWC objective scheme. A program was used to convert it so values at 5° latitude-longitude intersections were available over the Northern Hemisphere. For the Southern Hemisphere a mirror image of the field was used.

The first result, shown in figure 2, is a plot of the 500 mb. height at the poles for a 36 hour forecast in which the wind was initialized everywhere by use of,

$$\psi = gh/.0001 \tag{7}$$

$$u = - \partial\psi/\partial y \tag{8}$$

$$v = \partial\psi/\partial x \tag{9}$$

where ψ is the streamfunction and where these computations were done over the Northern Hemisphere and reflected into the Southern Hemisphere. The wind was set at 0 along the equator. Figure 3 shows the plot of the height values at a selected equatorial point. Immediately it is obvious that high to moderate frequency oscillations of large amplitude occur in the forecast. Realizing that straight use of the leapfrog time scheme is subject to the type of instability known as solution separation these runs were rerun using the stable two-level Euler-backward every 24 time steps to recycle or "tie together" the solutions. Improvement was noted at the poles but not enough to avoid the conclusion that the results are completely unacceptable for an operational model. The crude initialization here is at fault.

In figures 4 and 5 we show some similar results for runs in which the initialization was improved. The upper curves represent the cases in which the linear balance equations,

$$\nabla^2\psi + \nabla\psi\cdot\nabla f/f = g\nabla^2 h/f \tag{10}$$

$$\nabla^2 h = (f\nabla^2\psi + \nabla f\cdot\nabla\psi)/g \tag{11}$$

were used to define the initial fields. Equation 10 was used from latitude 30° to the pole. Equation 11 was used from latitude 20° to the equator. At latitude 25° a blend was used. For "observed" ψ values in the tropics equation (7) was used. This is permissible as this work is not concerned with verification of forecasts per se, but rather the question of initialization. Comparison of the upper curves of figures 4 and 5 to the curves in figures 2

and 3 shows immediately improvement in the sense that the amplitudes of the higher frequency motions are only one-third as great as they were in the former runs.

The lower curves in figures 4 and 5 represent the situation where an iterative proceedure was used in addition to the solution of equations (10) and (11) to initialize the forecast. What was done here simply was to run the equations alternately forward and backward six steps (now properly "iteration" rather than "time" steps), allowing the variables to freely change. Also during this proceedure the Euler-backward time differencing scheme was used. No restoration was used here so no constraint is placed on the adjustment mechanism. The process was run the equivalent of only 18 hours. Note the initial height value for the equatorial point changes about seven meters. The results are excellent.

However, the situations shown in these curves are still rather ideal. In order to test the process under more realistic conditions several experiments were designed to simulate the incorporation of observed data, to simulate the effects of large scale heating and friction and to include an "observed" wind containing divergence in the tropics.

The incorporation of observed data gives rise to the restorative feature of the iterative process. The results shown in the lower curves of figures 4 and 5, though excellent, do suffer from the lack of restraint during the iterative proceedure since the initial "observed" values of the mass or wind may be changed more than desired. Therefore, during the process, after each normal iteration of equations (1), (2), and (3), the following is added,

$$uh = (1-k_u)uh^* + k_u\, hu_o \tag{12}$$

$$vh = (1-k_v)vh^* + k_v\, vh_o \tag{13}$$

$$h = (1-k_h)h^* + k_h\, h_o \tag{14}$$

where the asterisk refers to the values of the variables computed from equations (1), (2), and (3) and the subscript o refers to the "observed" value of the variable. The k's are a function of latitude. k_u and k_v were set at .5 from latitude 20° S to 20° N, 0 from 40° to the pole and a linear variation between 0 and .5 between latitude 20° and 40°. k_h was set at .5 above and below latitude 40° N and S, 0 between latitude 20°S and 20° N and a linear variation between 20° and 40°. Figure 6 shows the result

of the forecast run. The upper curve is for the polar point(s), the lower curve for the same equatorial point as was used in the previous figures. A very slight deterioration in the results when compared to the lower curves in figures 4 and 5 is apparent. This is expected because restraint is being placed on the efficiency of the adjustment. Nevertheless, these results are still far superior to the results represented by the upper curves of figures 4 and 5.

Some comment is necessary concerning the particular coefficients used. Independent runs by the author and others have indicated that for a barotropic model in which only the very high frequency external gravity waves are present too much interference with the adjustment mechanism is undesirable as only the damping effect of the Euler-backward time scheme may be retained on the high frequency motions. Therefore, coefficients greater than .5 are not recommended. But with baroclinic models (see the reference to Mesinger), higher coefficients may be allowable as the dominant internal inertia-gravity waves are of lower frequency.

The next set of experiments concerned the inclusion of heating and friction effects into the initialization proceedure. Strictly speaking there can be no heating with a barotropic model but the effect may be simulated by a systematic addition or subtraction of height as a function of latitude or some other factor at each time step. For this we used,

$$H = 2 \times 10^{-8}(h)\ (.5 - |\sin \phi|)\ . \qquad (15)$$

For friction,

$$F_u = -.00003\ u\ , \quad F_v = -\ .00003\ v \qquad (16)$$

was used. In figure 7 results from a run initialized by use of equations (10) and (11) only are shown in which the expressions in (15) and (16) were added to the forecast equations. The amplitudes of the high frequency motions are very similar to those in the upper curves of figures 4 and 5. It is true that here total energy is apparently declining as the polar height rises over the 36 hour period and the equatorial height falls but again as the concern of these experiments is the reduction of the amplitude of the high frequency motions this decline in the total energy is not crucial. In figure 8 results are shown where the initialization was done as in the case shown in figure 6. No attempt is made to include the effects of the heating or friction terms

in the initialization process, that is to initialize the large scale divergence which would be in balance with these terms. Except for the effect of the heating and friction during the forecast there is nothing new here. These curves reproduce essentially the curves from figure 6.

To include the effects of the heating and friction terms into the restorative-iterative proceedure it must be understood that the processes of geostrophic adjustment and adjustment to the heating and friction terms are somewhat different in nature. For example, the equations can be run alternately forward and backward since the natural adjustment mechanism is dependent on the dispersive nature of the gravity-inertial waves which travel in all directions. Advection is not of prime importance. With heating and friction, however, there is no reason to run forward and backward as this would cancel the effects of these external forces completely. Therefore, some splitting of the iterative proceedure is strongly indicated. Note also that in the quasi-geostrophic theory the form of the omega equation suggests that the effect of heating and friction might be solved for completely separate from the part of the process in which geostrophic adjustment is important. Several variations of such a divided process were tried. The best result was obtained when first the restorative-iterative process was run as described before, but then before the forecast was begun the finite difference versions of,

$$d(uh)/dt = -\ kuh \tag{17}$$

$$d(vh)/dt = -\ kvh \tag{18}$$

$$dh/dt + h\nabla\cdot\mathbb{V} = H; k \equiv +\ .00003 \tag{19}$$

were run in a forward sense only with the restoration being done as indicated in equations (14), (15), and (16) after each step. k_u, k_v, and k_h were set equal to .5 at all latitudes during this part of the process and the restoration was made not to the original values of the variables but to the balanced values achieved at the conclusion of the adiabatic part of the proceedure. Only three hours of additional iterations were needed before no further changes in the height values were noted. Figure 9 shows results of the forecast. Differences with figure 8 are quite small though in the print-out of the entire field differences near five meters are noticeable at many points from the run in which the initialization was completely adiabatic.

Finally one question remains. If observations of tropical winds are adequate to be meaningfully analysed as has been assumed here, in reality they may contain some divergence not in any balance with the mass. That is the time change term may well be of the same order of magnitude as are other terms in the equations. Quasi-geostrophic theory, in fact, gives us little guidance in the low latitudes concerning these matters.

We created arbitrarily an "observed" divergent wind in the tropics by means of,

$$uh_d = 2h(\cos\ \pi(I-1)/9\ )(\cos\ \pi(18-J)/10) \tag{20}$$

where I ranges from 1 to 36 and the equatorial value of J is 18. Above and below latitudes 25° N and S uh_d was set at 0. In figure 10 the results at our points are shown where the model was initialized as for the case shown in figure 9, but at the commencement of the forecast uh_d was added to uh. The curve for the polar point(s) is identical to the polar curve in figure 9, but the curve for the equatorial point is considerably changed. The amplitude of the large oscillation between hour 12 and 28 is nearly doubled. Of course, this result is not unexpected. A question of convenience now arises. To what extent, if any, is it necessary to divide the observed wind into a divergent and non-divergent part to use the initialization proceedure in the tropics? In figure 10 the process was run with the restoration made to the non-divergent part of the wind during the adiabatic part of the process. In figure 11, on the other hand, results are shown in which the initialization proceedure was started with the total wind as defined from equations (20) and (7) and in which the restoration used the total wind. Several variations were tried as well, but all of the results varied negligibly from those shown in figure 11 and figure 10. Therefore, we have verified that our restorative-iterative process remains very convenient in the sense that total winds may be used without any preprocessing into divergent and non-divergent components.

4. Conclusions

We conclude from these experiments that a mathematically simple proceedure for initializing global primitive equation models is quite feasible given adequate observations of the mass in the temperate latitudes and the wind in the tropical latitudes. The proceedure is entirely consistent with the forecast equations and can be extended easily to baroclinic models. It can be extended to the four dimensional situation. There is no reason why this proceedure can not take into consideration a mixed situation in which both

wind and mass observations exist in a given area but may not be adequate over some entire region. The restoration coefficients can be varied. Thus if observed winds were analysed over the U.S. and Canada they could be taken into account in that particular area. The whole proceedure will soon be feasible operationally as computer technology is so rapidly advancing.

Appendix A

Finite Difference Equations

The difference equations corresponding to equations (1), (2), and (3) are,

$$\frac{\Delta(uh)_{ij}}{\Delta t} - \frac{1}{a\cos\phi_j}\;\frac{(u_{ij}+u_{i+1j})\;uh^*_{i+\frac{1}{2},j} - (u_{ij}+u_{i-1j})\;uh^*_{i-\frac{1}{2},j}}{2\,\Delta\lambda}$$

$$+\;\frac{(u_{ij}+u_{ij+2})\;vh^*_{ij+1}\cos\phi_{j+1} - (u_{ij}+u_{ij-2})\;vh^*_{ij-1}\cos\phi_{j-1}}{2\,\Delta\phi} \qquad \text{(A.1)}$$

$$-\;\frac{u_{ij}vh_{ij}\tan\phi_j}{a} - f_j\,vh_{ij} = -\,\frac{gh^*_{ij}}{a\cos\phi_j}\;\frac{h_{ij}-h_{i-ij}}{\Delta\lambda}$$

$$\frac{\Delta\,(vh)_{ij}}{\Delta t} - \frac{1}{a\cos\phi_j}\;\frac{(v_{ij}+v_{i+1j})\;uh^*_{i+\frac{1}{2}j} - (v_{ij}+v_{i-1j})\;uh^*_{i-\frac{1}{2}j}}{2\,\Delta\lambda}$$

$$+\;\frac{(v_{ij}+v_{ij+2})\;vh^*_{ij+1}\cos\phi_{j+1} - (v_{ij}+v_{ij-2})\;vh^*_{ij-1}\,\mathrm{ocs}\,\phi_{j-1}}{2\,\Delta\phi} \qquad \text{(A.2)}$$

$$+\;\frac{u_{ij}\,uh_{ij}\tan\phi_j}{a} + f_j\,uh_{ij} = -\,\frac{gh^*_{ij}}{a}\;\frac{h_{\ell-1j+1}-h_{\ell-1j-1}}{\Delta\phi}$$

$$\frac{\Delta h_{ij}}{\Delta t} = -\,\frac{1}{a\cos\phi_j}\;\frac{uh_{i+1j}-uh_{i-1j}}{\Delta\lambda} + \frac{vh_{\ell j+1}\cos\phi_{j+1} - vh_{\ell j-1}\cos\phi_{j-1}}{\Delta\phi} \qquad \text{(A.3)}$$

In these equations the following convention has been used. In Fig (A-1) the configuration and indexing of the mass and wind variables is displayed. Therefore, the index ℓ in equations (A.2) and (A.3) is i itself if j is odd and i+1 if j is even. Also the following definitions apply.

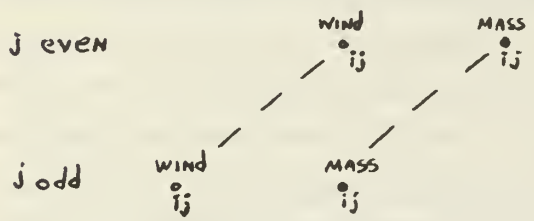


figure A-1

$$\left[\begin{pmatrix}u\\v\end{pmatrix} h\right]_{ij} \equiv \begin{pmatrix}u\\v\end{pmatrix}_{ij} (h_{ij} + h_{i+ij} + h_{l-1j+1} + h_{l-1j-1})/4 \qquad \text{(A.4)}$$

$$\left[\begin{pmatrix}v\\u\end{pmatrix} h\right]^*_{i+\frac{1}{2}\,j} \equiv \left[\begin{pmatrix}v\\u\end{pmatrix} h_{ij} + \begin{pmatrix}v\\u\end{pmatrix} h_{i+1j} + \begin{pmatrix}v\\u\end{pmatrix} h_{lj+1} + \begin{pmatrix}v\\u\end{pmatrix} h_{lj-1}\right]/4\,. \qquad \text{(A.5)}$$

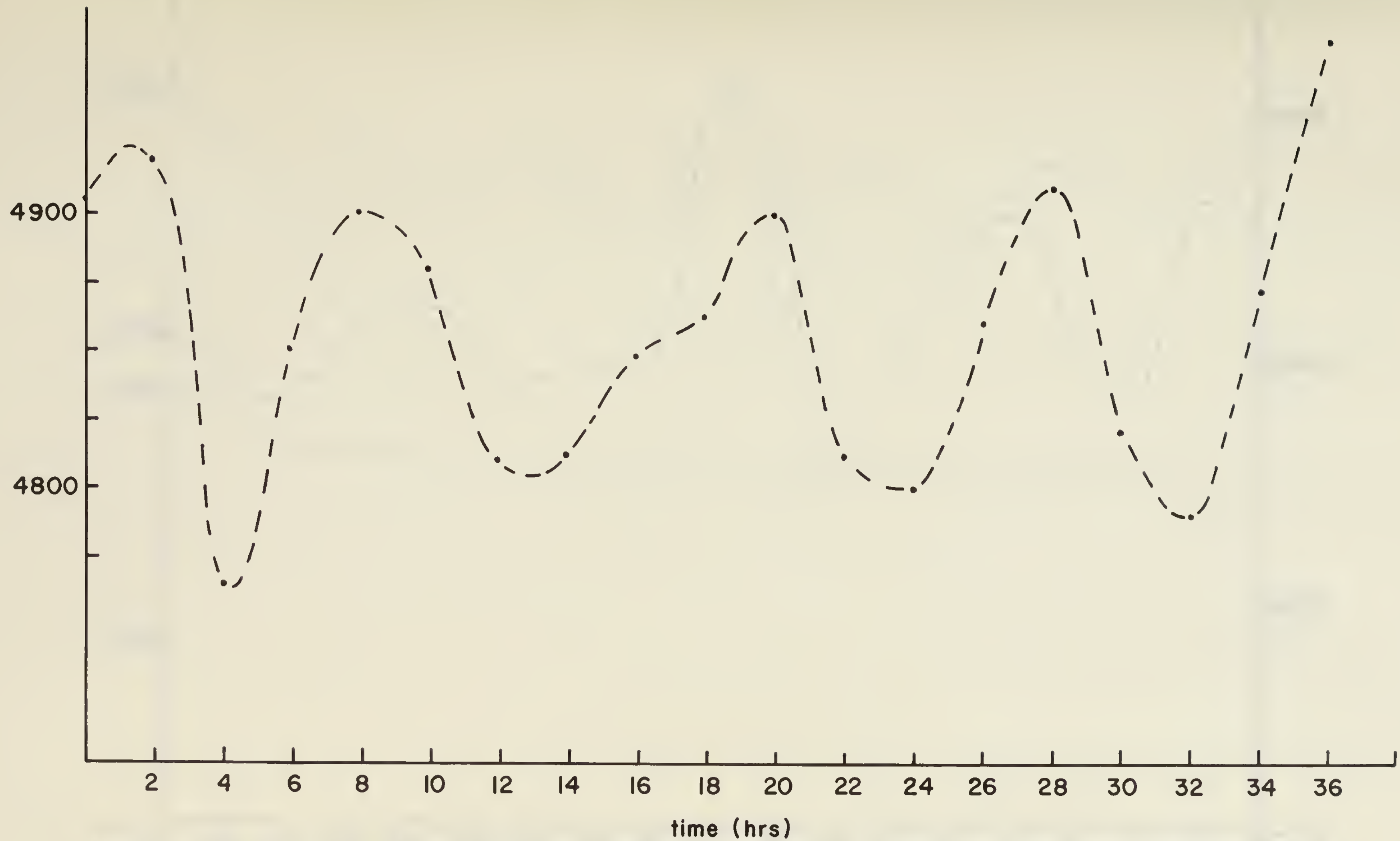
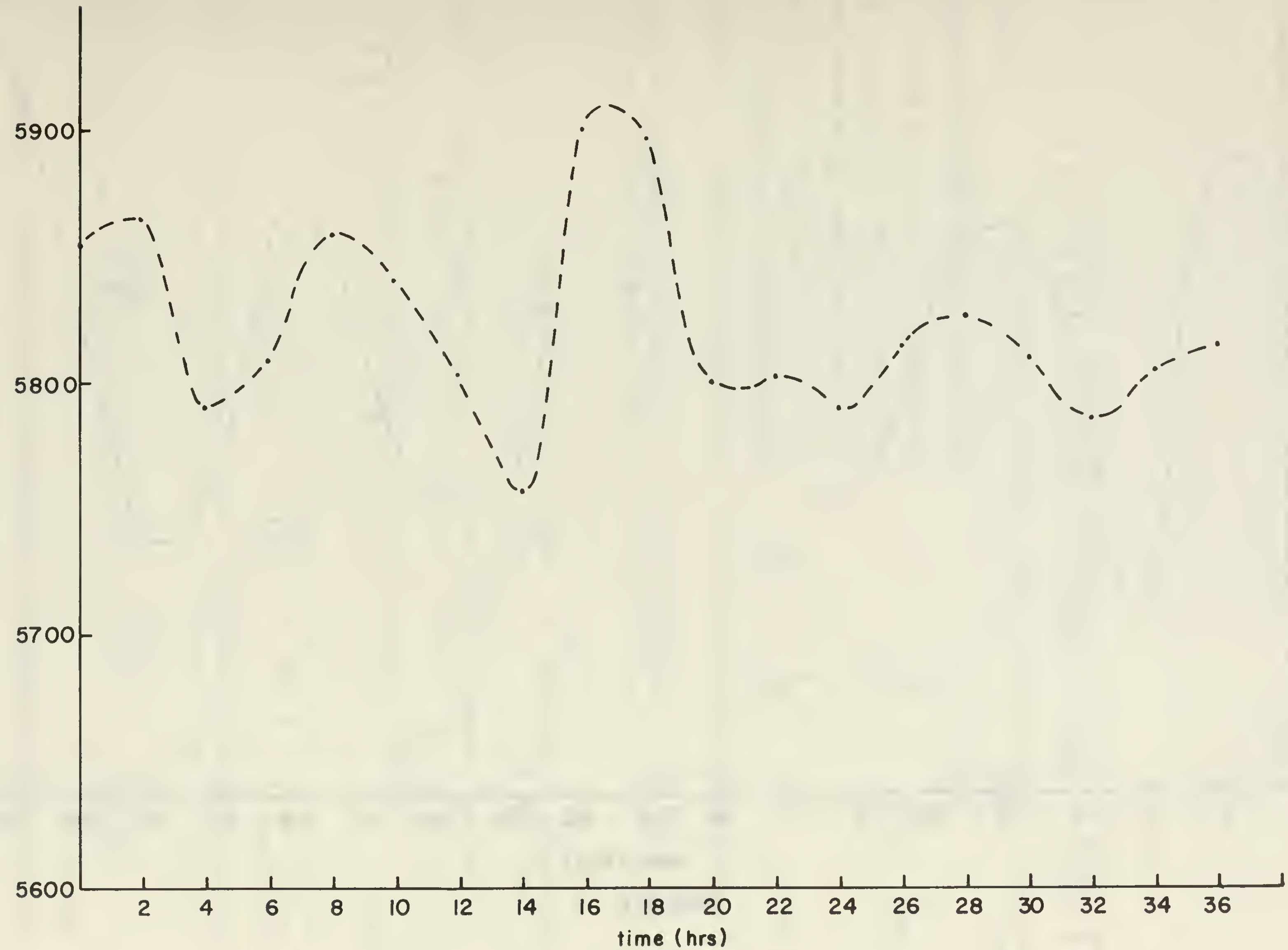


FIGURE 2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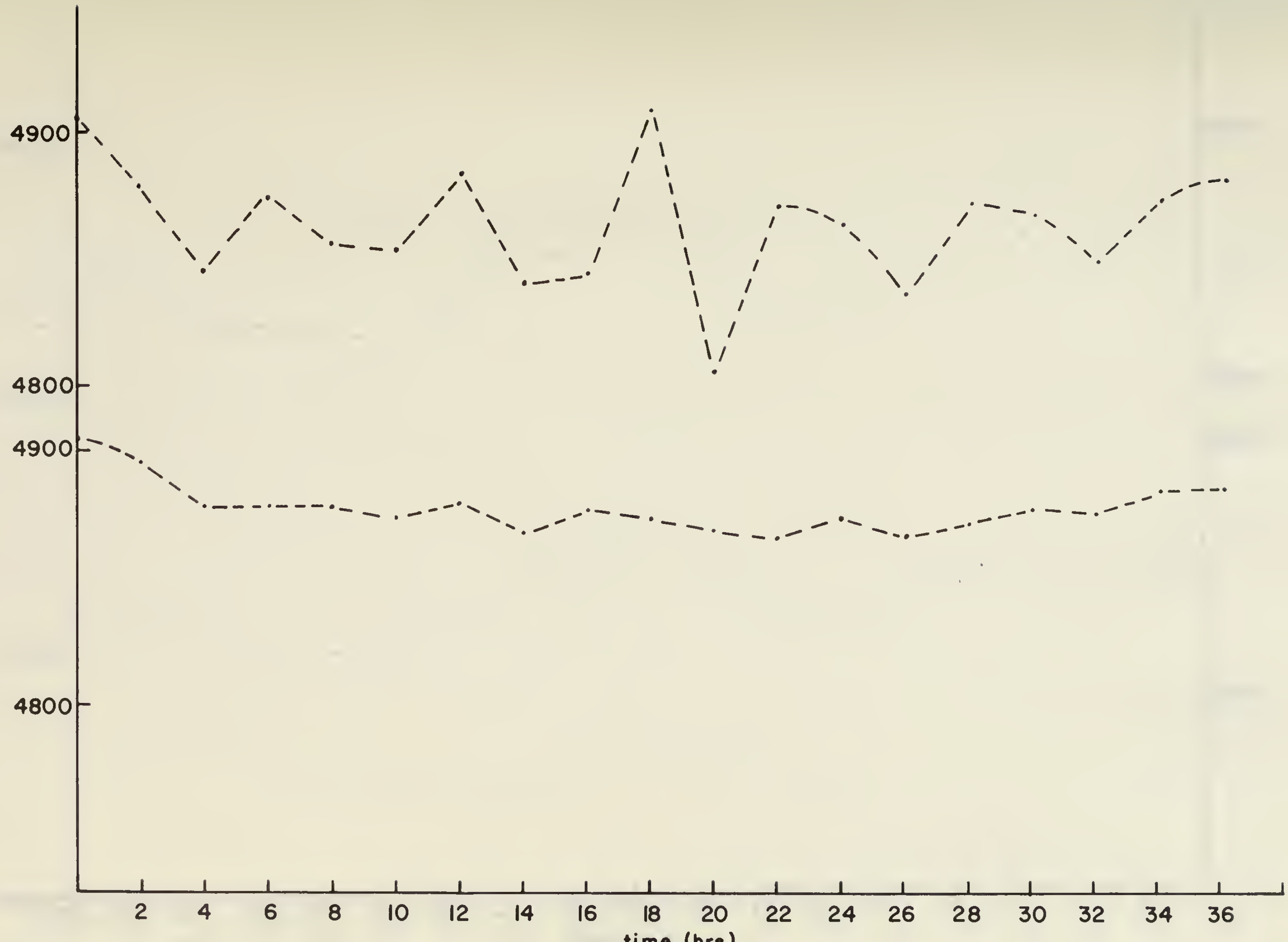
time (hrs)

FIGURE 3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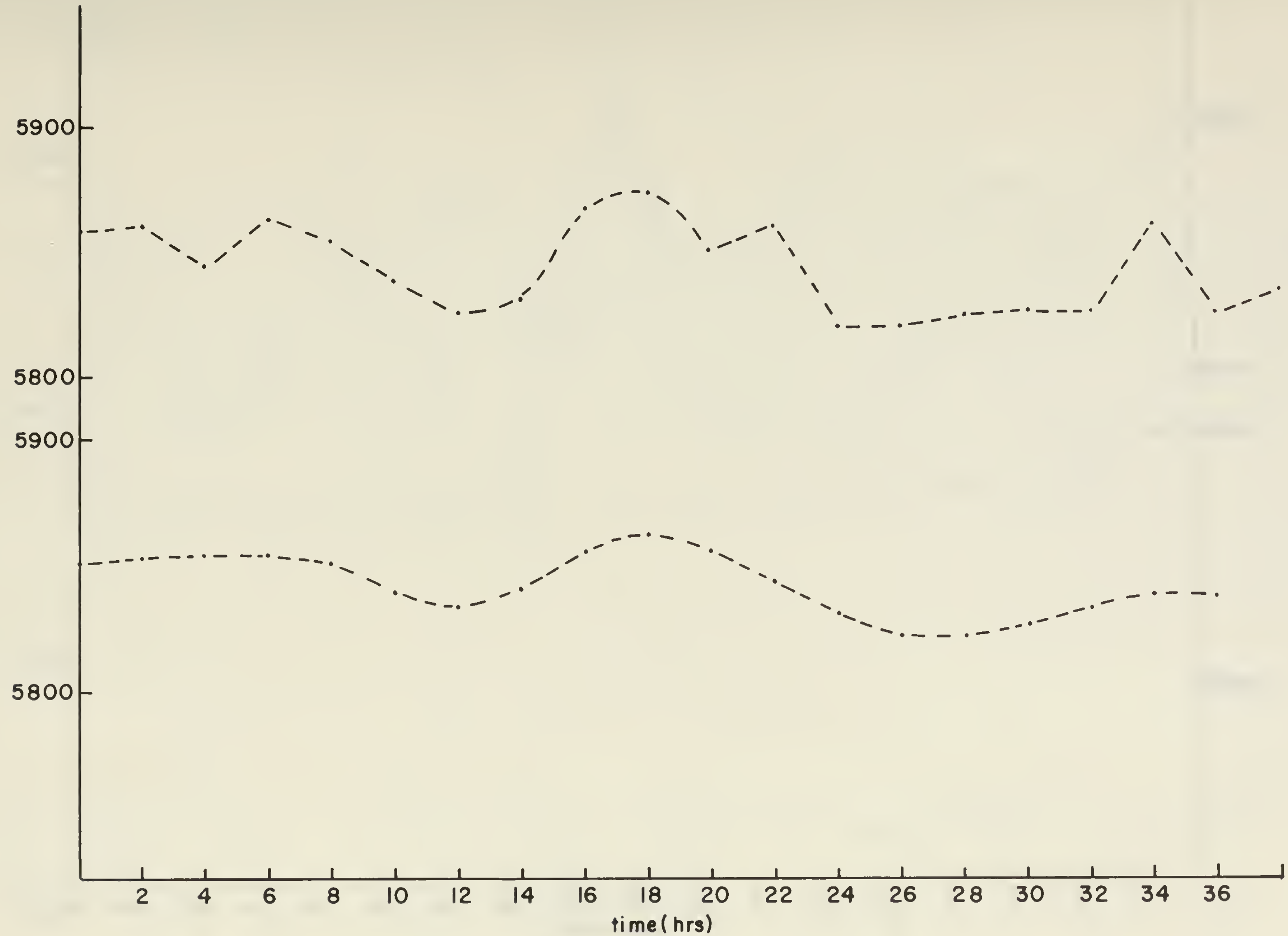
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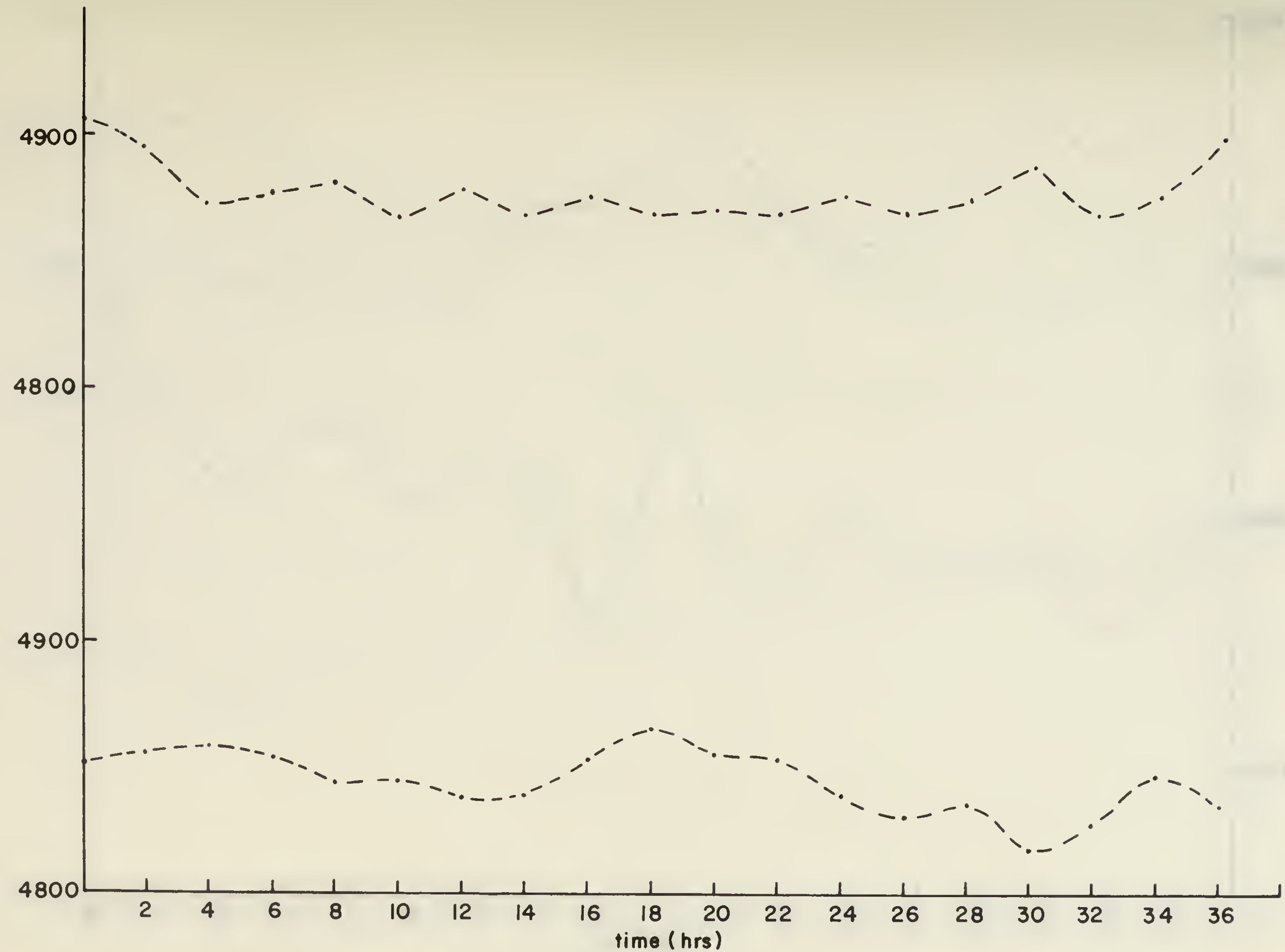
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FIGURE 6

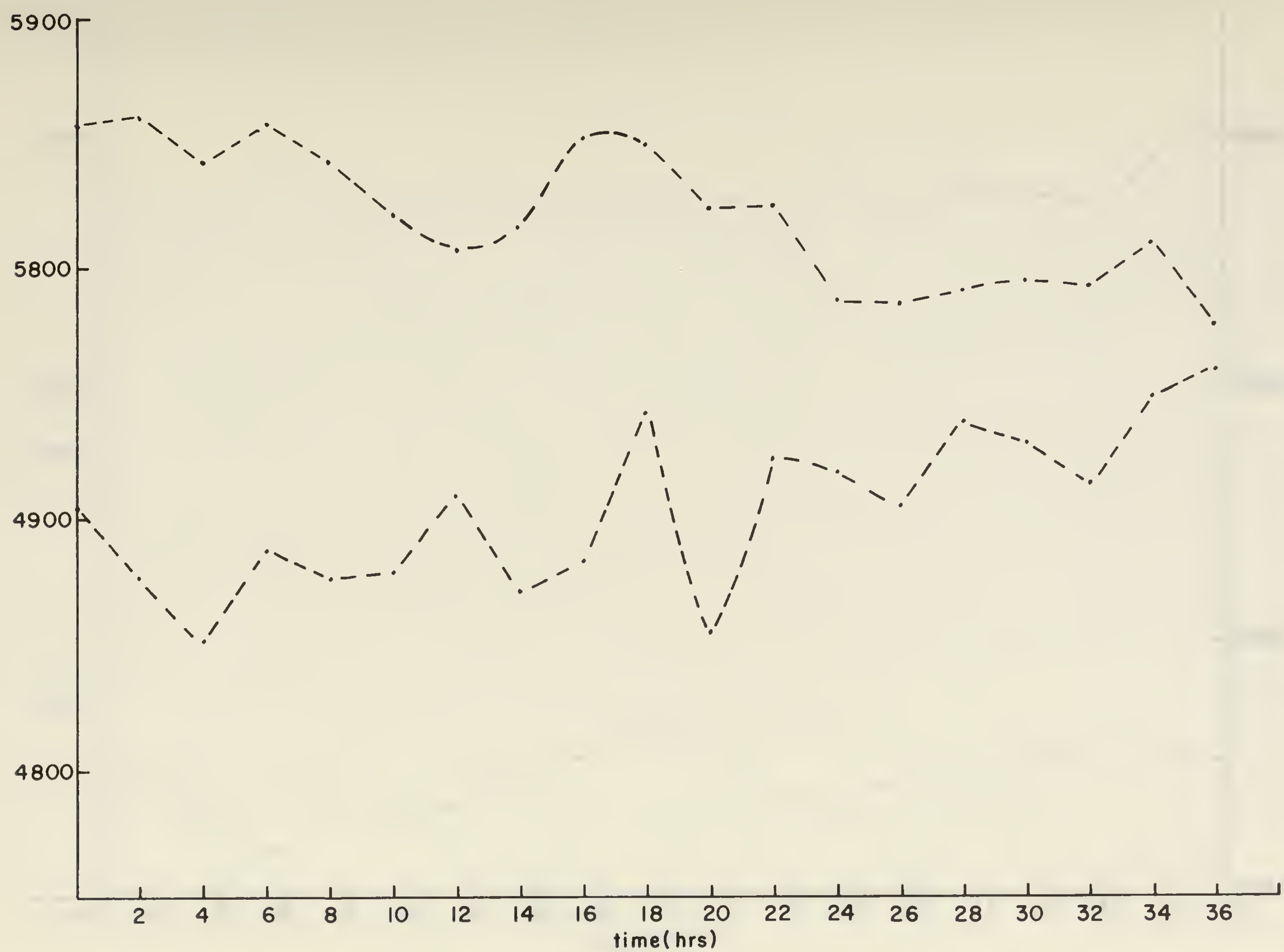
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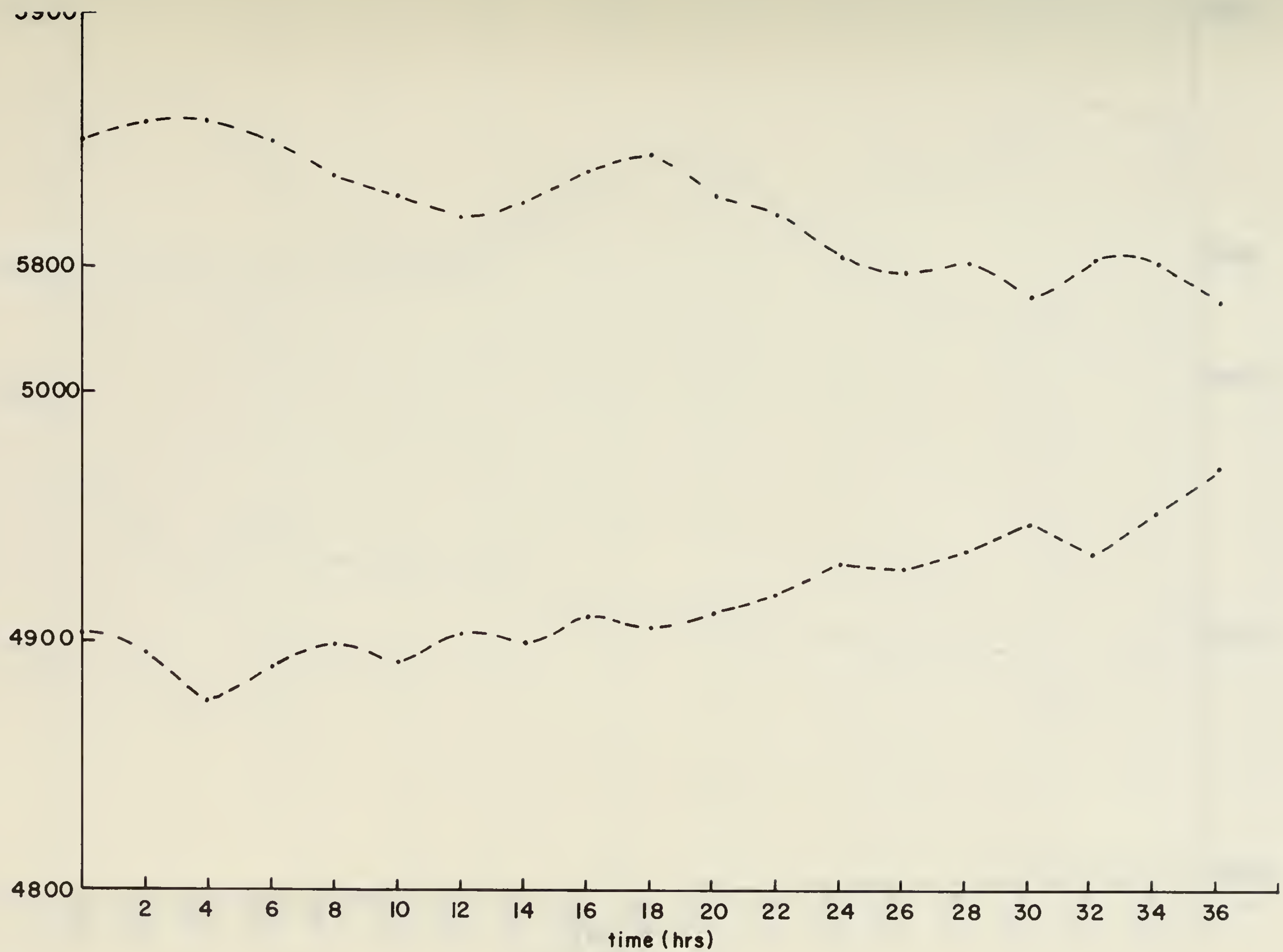
FIGURE 7



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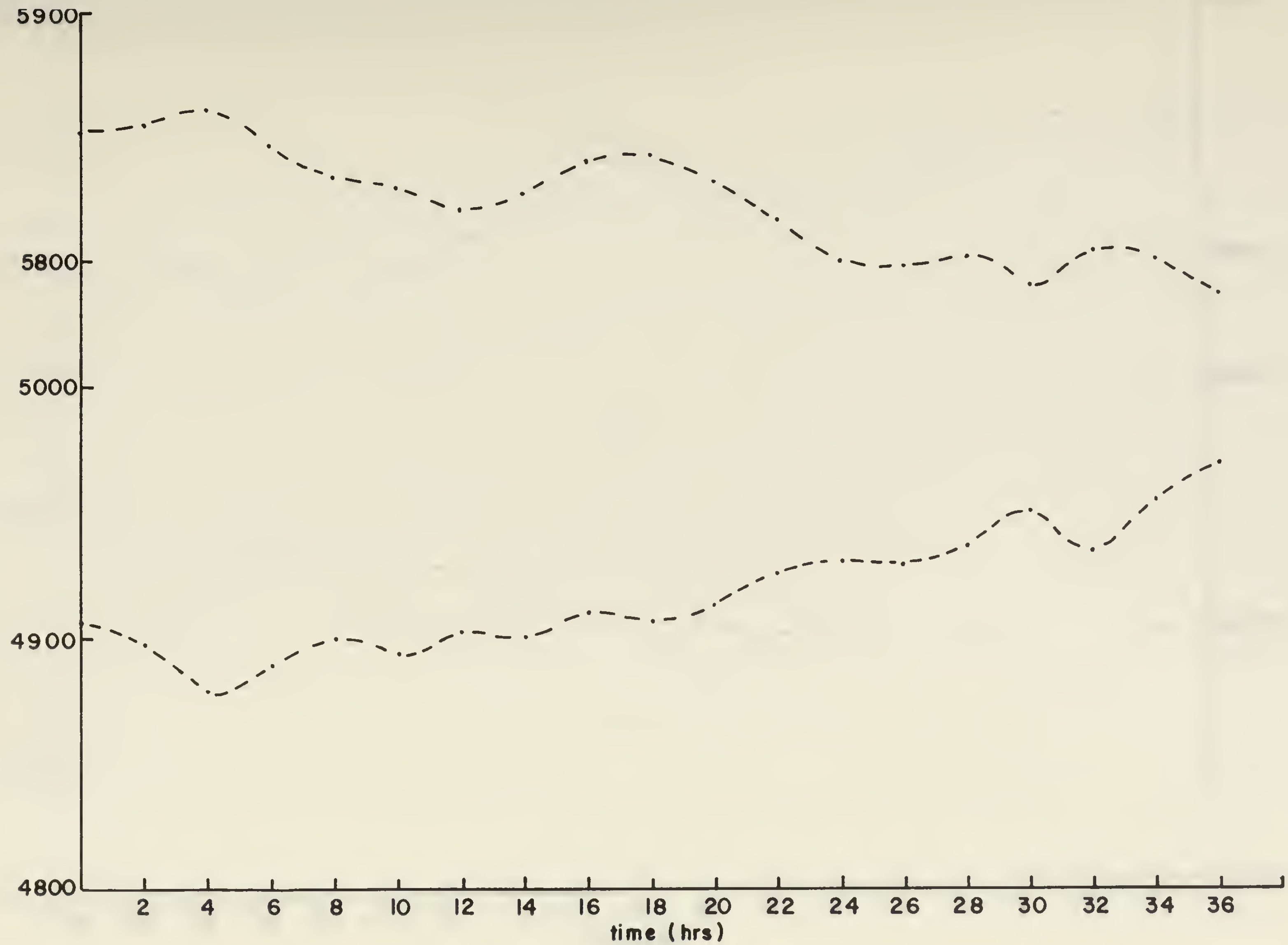
time (hrs)

FIGURE 8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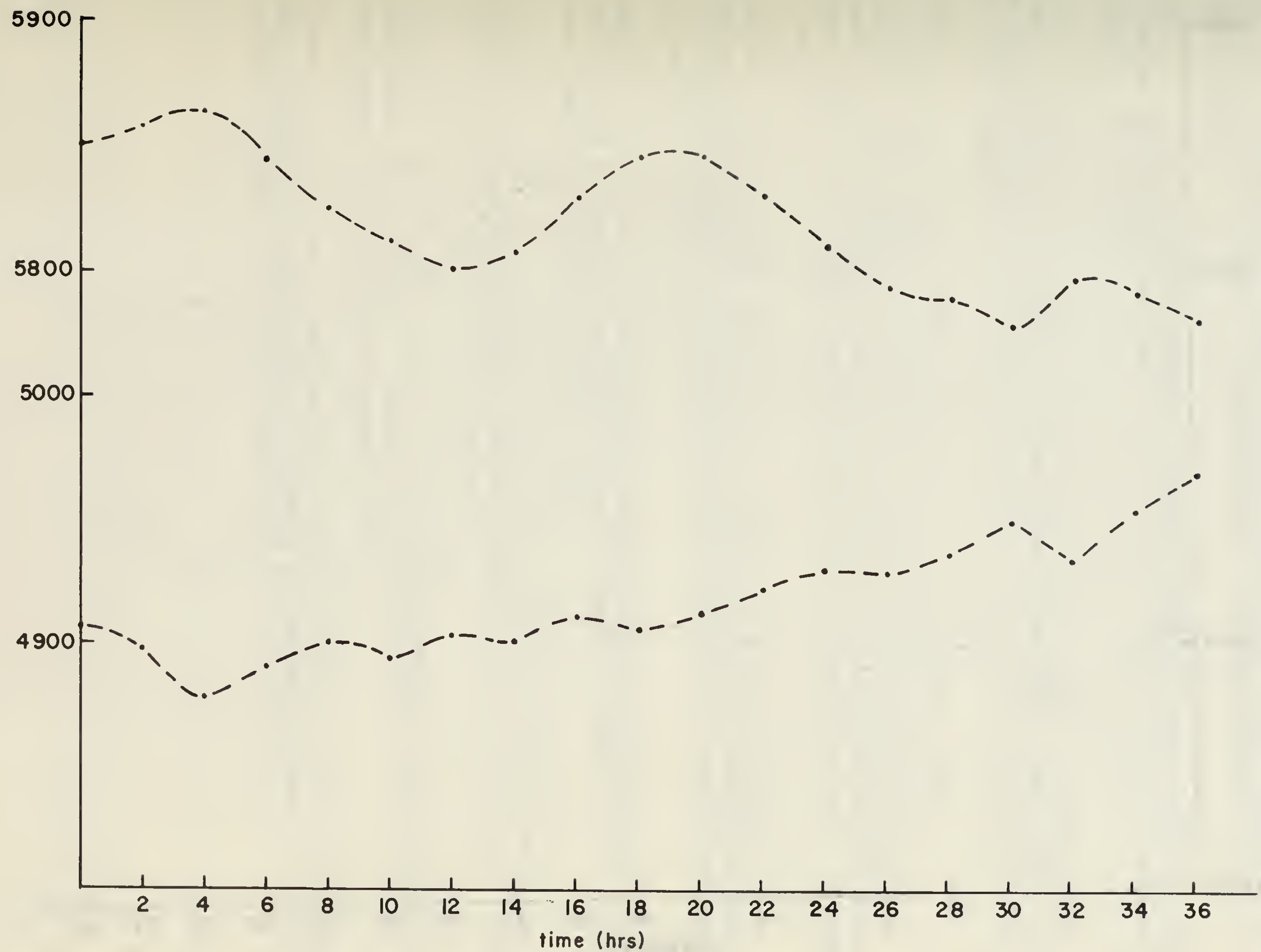
time (hrs)

FIGURE 9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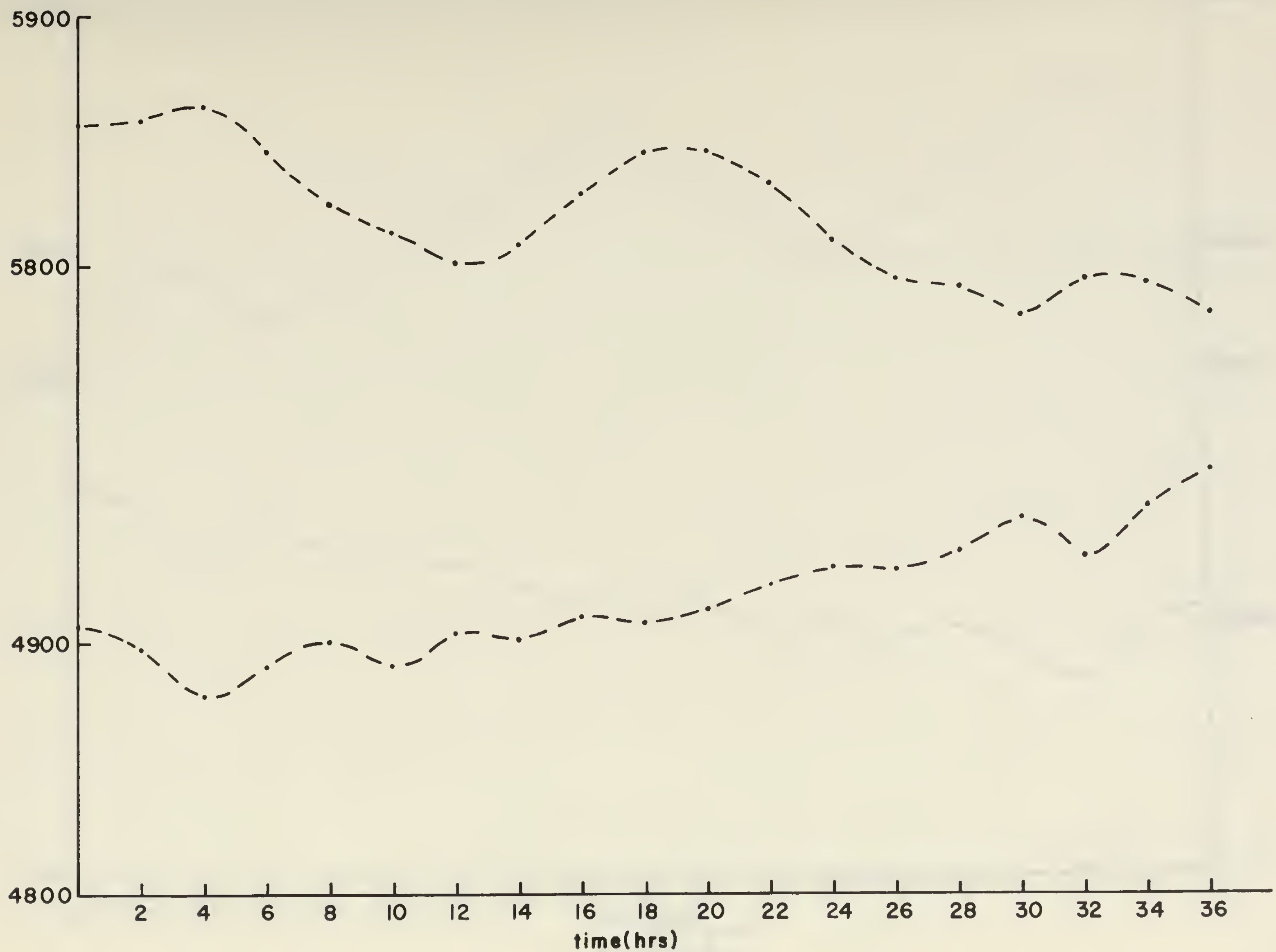
time (hrs)

FIGURE 10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time(hrs)

FIGURE II

Legends for Figures

Figure 2. Plot of 500 mb height at pole during 36 hour forecast initialized everywhere with first order quasi-geostrophic wind and analysed 500 mb height field.

Figure 3. Plot of 500 mb height at selected equatorial point during 36 hour forecast initialized everywhere with first order quasi-geostrophic wind and analysed 500 mb height field.

Figure 4. Upper curve, plot of 500 mb height at pole during 36 hour forecast initialized by solution of linear balance equations. Lower curve, plot of same but forecast initialized with addition of iterative proceedure with no restoration.

Figure 5. Same as in figure 4 but for selected equatorial point.

Figure 6. Upper curve, plot of 500 mb height at pole during 36 hour forecast in which restoration feature was added to the initialization proceedure. Lower curve, plot of 500 mb height at the selected equatorial point for same forecast.

Figure 7. Upper curve, plot of 500 mb height at selected equatorial point during 36 hour forecast initialized by solution of linear balance equations and in which friction and simulated heating is included. Lower curve, same as above for the polar point.

Figure 8. Upper curve, same as upper curve in figure 7 except initialization includes the restorative-iterative proceedure applied adiabatically. Lower curve, same as above for the polar point.

Figure 9. Upper curve, same as upper curve in figure 8 except that the restorative-iterative proceedure includes a diabatic part as described in text. Lower curve, same as above for polar point.

Figure 10. Upper curve, plot of 500 mb height at selected equatorial point initialized as in figure 9. "Observed" divergence added to wind in tropics. Lower curve, same as above for polar point.

Figure 11. Upper curve, same as upper curve in figure 14 except the divergent part of observed tropical wind was included in restorative-iterative initialization proceedure. Lower curve, same as above for polar point.

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13. ABSTRACT

A restorative-iterative proceedure is tested in initializing the height and wind fields for a global barotropic model. Real 500 mb. data is used as the basis of the initial height values in the mid latitudes and as the basis of the initial streamfunction values in the tropics. The proceedure is tested for the case of frictionless and adiabatic flow and for the case where friction and a simulated heating function is included. In addition, experiments were performed in which an "observed" divergent wind was added in the tropics. Results are very encouraging in the sense that the amplitudes of the external inertia-gravity motions excited due to initial imbalance between the mass and wind fields are reduced considerably with the use of the proceedure.

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